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Design optimization of stiffened composite panels with buckling and damage tolerance constraints

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ABSTRACT

The design of stiffened, composite wing panels must satisfy a range of requirements related to performance, economy and safety. In particular, the design must be damage tolerant to satisfy a number of different performance requirements for various states of damage. To obtain an optimum configuration that satisfies these requirements simultaneously, optimization code PANOPT was extended with a multi-model capability. First, the effect of damage tolerance constraints on postbuckled optimum design was established for blade- I- and hat-stiffened panels with stiffener flanges embedded in the skin. The "classical" order of efficiency for optimized panels designed for buckling alone (hats, I's, blades) was no longer valid, as the masses of the three panel types were approximately equal. To obtain realistic damage models, the failure mechanismms and damage tolerance of the panel concept with embedded stiffeners were determined in an experimental programme. Finally, the multi-model capability of PANOPT was demonstrated with the simultaneous optimization of an undamaged panel carrying design ultimate load, the same panel with a separated stiffener carrying design limit load, and the panel with a cut stiffener carrying seventy percent of the design limit load. An optimum design was found with an additional mass of only five percent compared to a panel optimized for the undamged case alone.

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Abstract

The design of stiffened, composite wing panels must satisfy a range of requirements related to performance, economy and safety. In particular, the design must be damage tolerant to satisfy a number of different performance requirements for various states of damage. To obtain an optimum configuration that satisfies these requirements simultaneously, optimization code PANOPT was extended with a multi-model capability. First, the effect of damage tolerance constraints on postbuckled optimum design was established for blade- I- and hat-stiffened panels with stiffener flanges embedded in the skin. The "classical" order of efficiency for optimized panels designed for buckling alone (hats, I's, blades) was no longer valid, as the masses of the three panel types were approximately equal. To obtain realistic damage models, the failure mechanisms and damage tolerance of the panel concept with embedded stiffeners were determined in an experimental programme. Finally, the multi-model capability of PANOPT was demonstrated with the simultaneous optimization of an undamaged panel carrying design ultimate load, the same panel with a separated stiffener carrying design limit load, and the panel with a cut stiffener carrying seventy percent of the design limit load. An optimum design was found with an additional mass of only five percent compared to a panel optimized for the undamaged case alone.

Introduction

The use of advanced composite materials, and in particular of carbon fiber reinforced epoxy material, has become a common factor even in the conservative, economy driven design environment of today's civil aircraft. Empennage structures of Airbus and Boeing aircraft, as well as wing sections of the ATR-72 commuter aircraft are but the first examples of primary aircraft structures made of these materials.

Originally, the appealing advantages of a higher specific strength and stiffness, as compared to the corresponding values for aluminum, made composite materials a seemingly superior solution for civil aircraft structures. Design procedures were aimed at achieving maximum structural performance. Wing and empennage panels, the first candidate structures to be made of composite materials, were optimized for buckling, and the potential to operate the panels into the postbuckling range was explored[1,2]. Design optimization codes developed for prismatic stiffened panels were often based on the efficient finite strip method. Examples are PASCO[3], VICONOPT[4], PANDA2[5] and PANOPT[6]. These optimization procedures can be used to pursue minimum weight designs by establishing an optimum set of pre-selected design variables, typically ply angles or ply thicknesses and plate widths. Constraints can be imposed on buckling loads, maximum strains, ply thicknesses and geometry. Generally, the design variables are continuous, so a rounding-up of ply thicknesses to integer values needs to be performed at the end of the optimization. With PANOPT it is possible to impose postbuckling constraints in addition to buckling constraints. During each optimization cycle, the exact postbuckling stiffness of a compression loaded, prismatic plate assembly can be computed at the initial buckling load. The computation is based on Riks' derivation for finite strip analysis[7], and Arendsen's elaboration and implementation in PANOPT[8]. In PANOPT, the

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postbuckling stiffness is assumed to remain constant with increasing load, and a maximum postbuckling strain range can be specified[6], or a Tsai-Hill failure criterion can be consulted in order to determine the maximum load of a particular design.

With the development of larger composite aircraft components it became apparent that fiber reinforced composite materials, just like baseline material "aluminum", are hampered by particular inherent weaknesses. Most manufacturing techniques for composite aircraft structures in use today, including the mature "prepreg/autoclave" technique, result in layered material build-ups. The dominant weakness of this material configuration is that impact damage, introduced accidentally during manufacture, operation or maintenance of the aircraft, may consist of delaminations between the layers. Delamination damage, when caused for instance by tools dropped at relatively low velocities, is difficult or even impossible to detect during visual inspections, but may increase in size under loading and lead to premature failure of the structure at loads below the design load. However, it is a requirement that aircraft structures, when containing invisible or Barely Visible Impact Damage (BVID), are able to carry the full ultimate design load[9]. Hence, the drive to design for optimum mechanical performance became the need to design for damage tolerance.

With an increased understanding of the failure mechanisms of composite panels, in particular of panels with impact damage, "damage tolerance" constraints can be taken into account in the optimization procedure. Such constraints can be imposed "manually", by restricting laminate composition and geometry. For instance, the limitation of axial stiffness of the skin to obtain a so-called "soft-skin" configuration, is known to result in a damage tolerant solution[10,11], in particular when combined with a well chosen stacking sequence[12]. However, the design optimization process can be strongly enhanced when design requirements for different severities of damage can be considered simultaneously in an optimization routine. This implies that several configurations of the same panel, representing the undamaged state as well as several damaged states, and possibly even several corresponding repaired states can be addressed simultaneously. To make this possible in an efficient way, PANOPT has been extended with a multi-model capability. The present study presents the steps that were taken in support of the development of this capability, demonstrates the use of this capability and illustrates a future development to include the capability to design for damage resistance in PANOPT as well.

Damage tolerance of stiffened panels

The design of stiffened panels for damage tolerance depends on the failure mechanisms that may occur. The damage tolerance of the soft-skin panel concept with doublers and discrete stiffeners (Fig. 1), as originally devised by Boeing[10], is thought to be achieved by the following features. As the 0-degree plies carry most of the (compression) load, panel failure is primarily governed by the failure of the 0-degree plies. When delamination damage is present, some of the 0-degree plies become unstable and bend or buckle, thereby escaping load. The resulting load eccentricity increases the loading of the adjacent 0-degree plies and invoke their premature failure, etc. For a damage tolerant panel design it is important to protect the 0-degree plies from damage in the first place, to limit load eccentricities by providing back-up bending stiffness to damaged 0-degree plies in the second place, and ultimately, to prevent the damage to spread from one load path to the next.

The soft skin concept, as shown in figures 1, is satisfying all these aspects. The 0-degree plies are concentrated in the stiffener and in the doubler, which are the added layers in the skin beneath the stiffener. The stiffener itself is protected from impact damage during service because it is positioned inside the wing. Hence, the vulnerable 0-degree plies are the plies in the stiffener flange and the doubler. The combination of base skin, doubler laminate and stiffener flange forms a laminate with maximum thickness for the load case and panel weight considered - all other laminates (of the skin between stiffeners and of the other stiffener sections) are thinner. Hence, this concept provides maximum protection to the critical 0-degree plies, as the minimum force to create damage is proportional with the laminate thickness[13]. Backup stiffness of the critical 0-degree plies is provided by the stiffener behind the doubler/flange area. Even when the first 0-degree plies, located in the skin near the flat side of the panel, bend or buckle out, the subsequent load eccentricity for the panel is limited because of the presence of the stiffener. Further, the spread of the damage may be limited because the load paths, which are the 0-degree dominated doubler/flange areas together with the rest of the stiffeners, are connected mainly by compliant ±45-degree plies.

In the present study on panel optimization for damage tolerance, a "flush-skin" concept (Fig. 2-4) was evaluated, which is easier to fabricate than the baseline configuration of figure 1, while most of the advantages with respect to damage tolerance were thought to be maintained. The flush-skin concept is also easier to interface with adjacent structures such as ribs, and to inspect and repair. In this concept, the critical load carrying plies are located in the stiffener flange, which is embedded in the middle of the skin laminate. The protection of these plies is not as effective as for the baseline panel, because the laminate is thinner than the total laminate of base skin, doubler and stiffener flange of the baseline configuration. However, the critical plies have an equal back-up stiffness provided by the stiffeners, and are also isolated from each other by the soft-skin laminates. An advantage of the flush-skin concept over the baseline concept may be that it is thicker overall, thereby reducing the occurrence of impact damage in the skin between stiffeners.

The effect of damage tolerance constraints on design

The effect on structural efficiency of imposing damage tolerance constraints in addition to buckling and postbuckling constraints was evaluated for three flush-skin designs of panels with blade-, I-, and hat-stiffeners (Fig. 2-4). To obtain optimized designs with the damage tolerance characteristics discussed above, the following restrictions were imposed on the various laminates present in the panels. The two symmetric stiffener laminates making up one blade- or I-stiffener, and the continuous stiffener laminate making up one hat-stiffener, are designed with ±45 degree sublaminates at the outside, one 90-degree laminate in the center and two equal stacks with a variable number of 0-degree plies positioned in between. The stiffener core laminates of the blade- and I-stiffeners consist of a variable number of 0-degree plies. The top of the hat-stiffener may have more 0-degree plies than the continuous hat-stiffener laminate. The symmetric skin core laminate must be soft and equally thick as the stiffener flange laminate. It has a variable number of 45-degree plies and a single 90-degree ply in the center. However, because the number of plus and minus 45-degree plies must be equal, and the laminate must be symmetric, which limits the options to steps of 4n ±45 plies, 0-degree plies may be added for intermediate laminate thickness values. The skin face laminates must also be soft, but should contain at least one 0-degree ply. Therefore, the face laminates considered have a variable number of ±45-degree plies at the outside of the skin, and a 0/90/0 laminate at the inside, adjacent to the skin core laminate and the stiffener flange. In addition to these ply thickness design variables, geometric design variables were defined, such as the stiffener pitch and the stiffener geometry (see Figs. 2a-4a).

The panels were optimized for a Design Ultimate Load (DUL) of 2000 N/mm at a panel length of 550 mm. To compensate for the reduced panel stiffness due to local buckling, global buckling loads (Euler and torsional buckling), which are computed by PANOPT for the unbuckled state, were constrained to be higher than 2400 N/mm. The (additional) postbuckling strain at 2400 N/mm was constrained to be no more than 1.25 times the prebuckling strain, an empirical value, to ensure that the designs obtained would not buckle below Design Limit Load (DLL). The axial strain of the panel ($\Delta l/l$) was constrained to be no more than 0.0055 at DUL, which reflects the expected damage tolerance of the design. The basic material properties used were: E_x = 124 GPa, E_y = 9 GPa, υ_{xy} = 0.3, Gxy = 5.1 GPa and t = 0.181 mm. The final designs after laminate round-up are shown in figures 2b-4b. The critical constraints for the blade-stiffened design were the global buckling load and the minimum pitch, for the I-stiffened design the maximum strain and the maximum top width, and for the hat-stiffened design the maximum strain and the minimum skin between stiffeners. A full account of the optimization is described in reference 14.

A comparison of the three design concepts shows that their optimum weights are almost equal, which is contrary to "historical" results obtained when only buckling constraints are imposed. In the latter case, hat-stiffened panels were shown to be the most efficient, followed by I-stiffened panels, while blade-stiffened panels are the heaviest. By comparison, the more elaborate soft skin design concept with doublers (Fig. 1), in this case provided with I-stiffeners, which was optimized for the same constraints[12], weighs only 6 % less at 9.11 kg/m^2.

Damage scenarios and requirements

The blade-stiffened flush-skin design was further explored to see how representative damage scenarios can be modeled with PANOPT and what effect these damages may have on the optimized design. As PANOPT uses a finite strip buckling analysis routine, damages can only be modeled along the full length of the structure considered, which is often the length

between two ribs. However, this restriction is not too severe, as certification procedures generally require design for worst case damage scenario's, each scenario corresponding to a specific strength criterion. For instance, a panel with Non Detectable Damage must be able to carry the full Design Ultimate Load (DUL) just like an undamaged panel, while the required strength of a panel with Detectable Damage is no more than Design Limit Load (DLL). For Discrete Source Damage it is sufficient if the strength is at least 70 % of the Design Limit Load (DLL)[9].

Damage modeling in PANOPT

Two different models of damaged panels were considered, and their individually optimized configurations were compared to the optimized undamaged panel configuration (representing the case with Non Detectable Damage). The same design variables and constraints were used as for the study described above. However, the optimized undamaged configuration, shown in figure 5a, is slightly heavier than the one in figure 2b, because the minimum stiffener pitch was now required to be at least 150 mm. A Detectable Damage was modeled as one stiffener, entirely separated from the skin between two ribs, possibly as the result of a fabrication error. A Discrete Source Damage was modeled as a 5-stiffener panel with one completely cut (absent) stiffener-blade, possibly as the result of an impact by a turbine fan blade.

For the case of a separated stiffener, a single stiffener was required to carry the DLL of the entire stiffener pitch. An axial strain level of 0.0070 at DLL was allowed, which is a material constraint rather than a damage tolerance constraint, as damage is already present. A singular optimization of this configuration by itself resulted in a solution, found by increasing the blade and flange thickness of the stiffener (Fig. 5b). Although the cross section of the stiffener was the same as for the undamaged case (Fig. 5a), a thicker panel skin would be needed, resulting in a weight penalty compared to the optimum design for the undamaged configuration. The critical constraints were Euler buckling and local buckling.

The 5-stiffener panel with one missing stiffener-blade was required not to buckle in a single half-wave buckling mode below 0.7 DLL, as this might lead to a premature torsional buckling of the adjacent stiffeners (Fig. 6). This requirement by itself can be met by decreasing the stiffener height, while increasing the stiffener and skin thicknesses (Fig. 5c). The single half-wave buckling mode was the critical constraint. There is no weight penalty compared to the undamaged design, but the geometry is not at all in correspondence with the undamaged design. It is clear that by considering damage scenario's one by one, weight penalties would add up, while a simultaneous optimization for all scenario's will result in a more efficient design.

Failure modes

In order to investigate the feasibility of the embedded stiffener panel concept, and to establish likely failure modes due to Non Detectable Damage, a limited experimental program was carried out. Four small (450 mm long) 2- and 3-stiffener panels were manufactured according to the design of figure 2b, and were tested in compression, two with 25 J impact damage and two without damage. The panel design strain at Design Ultimate Load (DUL) was set at 0.0055, as mentioned earlier. The failure strains for the damaged panels were 0.0052 and 0.0054, just below the design strain. The failure strains for the undamaged panels were 0.0072 and 0.0055. The failure mechanism is explained in figure 7, which illustrates that in case of an undamaged panel, the discontinuity between stiffener flange and filler laminate may lead to a similar failure mode as the presence of impact damage. Due to lateral bending of the skin bays as a result of post-buckling, delaminations initiate and grow, leading to ultimate failure. These delaminations occur between the various components of the skin laminate: between filler, flange and cover laminates, just as in the case of a compression loaded specimen with impact damage. This explains the similarity between the failure strains of one of the undamaged panels and the damaged panels. For a redesign, to prevent failure below DUL for the Non Detectable Damage scenario considered here, the local buckling design load could be increased from 0.0037 to 0.0055, or the axial strain limitation, representing the expected damage tolerance, should be set at 0.0050 instead of 0.0055. Both solutions would lead to a weight penalty. A tapered stiffener foot would be beneficial, but would add to the fabrication costs. However, the tests revealed that the assumed failure strain and failure modes are realistic. The tests are reported in detail in reference 15.

Multi-model optimization

Considering the three analysis models simultaneously, which share the same design variables, but which are

each subjected to different constraints and boundary conditions, PANOPT's multi-model capability was used to determine the optimum configuration of the blade-stiffened panel, see figure 5d. The result satisfies all three requirements combined, and the final design carries a weight penalty of only 5 % compared to the undamaged case (Fig. 5a) alone. However, the design variables have changed considerably: the skin increases slightly in thickness and softens (less stiff), while the stiffener web increases in thickness and hardens (stiffer). Also, the stiffener height decreases while the stiffener flange width increases. Only the stiffener pitch remains equal to the constrained minimum pitch, as for the undamaged case. The results shown in figure 5 were obtained after rounding-up to integer plies, followed by a final optimization with the geometric design variables alone. The critical constraint for the undamaged configuration is a global buckling mode, for the case of the separated stiffener it is a local buckling mode with three half waves, and for the case of the cut stiffener blade it is a local buckling mode with two half-waves. The optimization is described in more detail in reference 16.

Future work

The multi-model optimization capability can also be used to include damage repairs. When repair is needed, the DUL capability should be restored. Bolted patch repair, as described in reference 17, can easily be modelled in PANOPT. Another scenario (model) that is being included in PANOPT is that of a simulated impact event. Several studies[12,18] have indicated that the impact event, and even the resulting damage is often comparable to quasi-static lateral indentation. PANOPT is presently being extended so the peak force corresponding to a given "impact energy" can be computed. This impact force can be constrained to be smaller than an impact force threshold at which damage is being generated[13]. In this manner, stiffened panels can be optimized to be damage resistant. Damage resistance is then pursued by the absorption of impact energy, either by elastic response or by sheer plate thickness. The stiffener spacing is an important parameter in this respect.

Conclusions

PANOPT, an optimization code for the design of prismatic, stiffened, composite panels has been extended with a multi-model capability. Thereby, a panel design can be optimized while simultaneously considering a range of damage states, each with the corresponding design requirements. Such damage states can be the Non Detectable Damage, Detectable Damage, and Discrete Source Damage specified by the FAA. The influence of damage tolerance constraints on design was evaluated, and was shown to reduce the advantages of particular design concepts optimized for buckling alone. The modeling of damage scenario's in a finite strip analysis was demonstrated, showing that the limitation to prismatic damage configurations, governed by the finite strip method, do not preclude the possibility to model the worst case scenario's to be considered for certification. Failure mechanisms were established experimentally for the panel concept with embedded stiffener flanges, that was used in the optimization exercises. Results were presented of a simultaneous design optimization for for the undamaged state and for two damage scenario's (models) for a blade-stiffened design. A weight penalty of no more than 5 percent was achieved, relative to the design optimized for the undamaged state alone. It was shown how the design variables changed due to the simultaneous optimization. Future work will focus on another scenario, that of the infliction of impact damage, based on an impact force threshold criterion. It is believed that this capability will facilitate the design for damage resistance.

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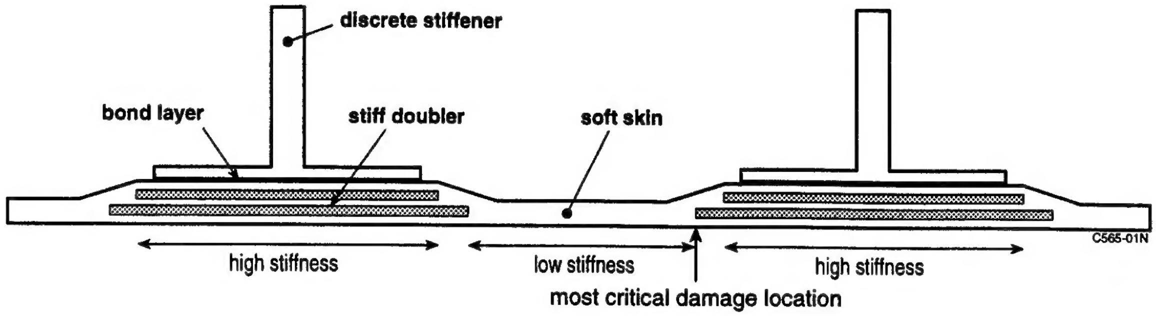


Fig. 1 Soft skin panel concept (baseline)

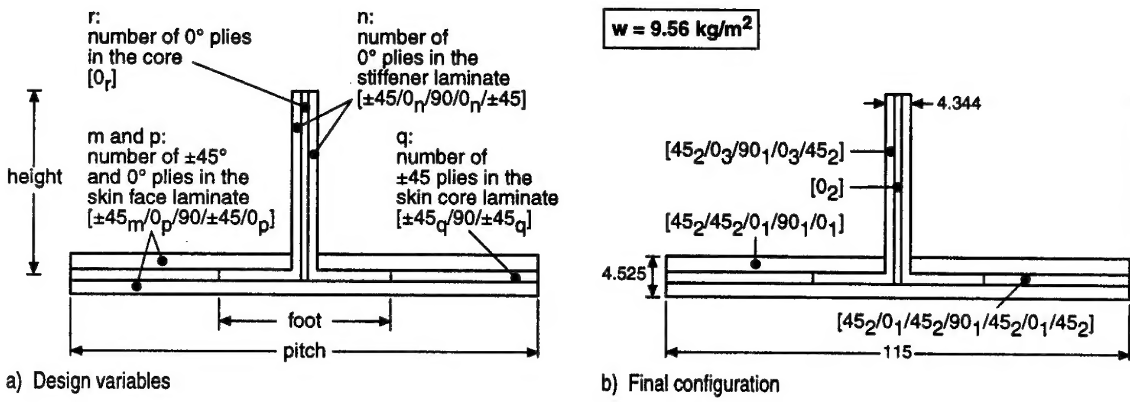


Fig. 2 Blade-stiffened, flush-skin design (dimensions in mm)

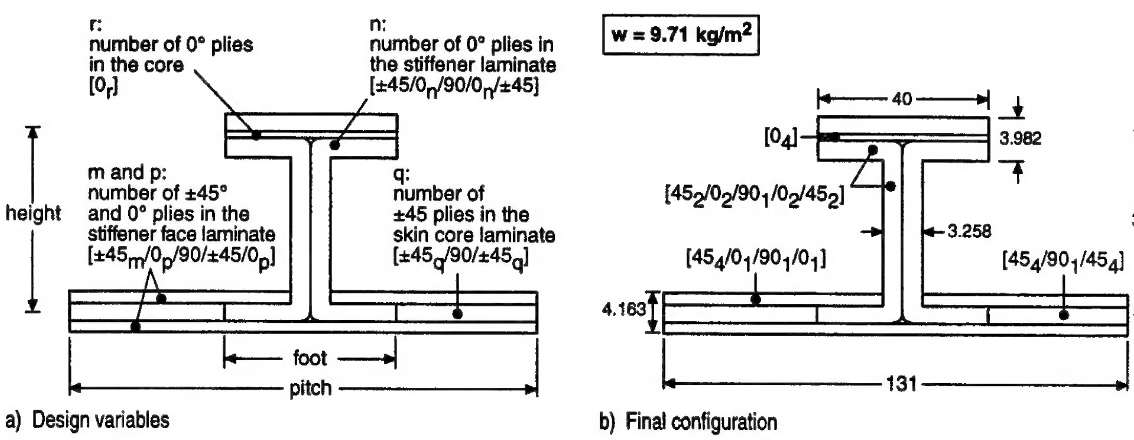
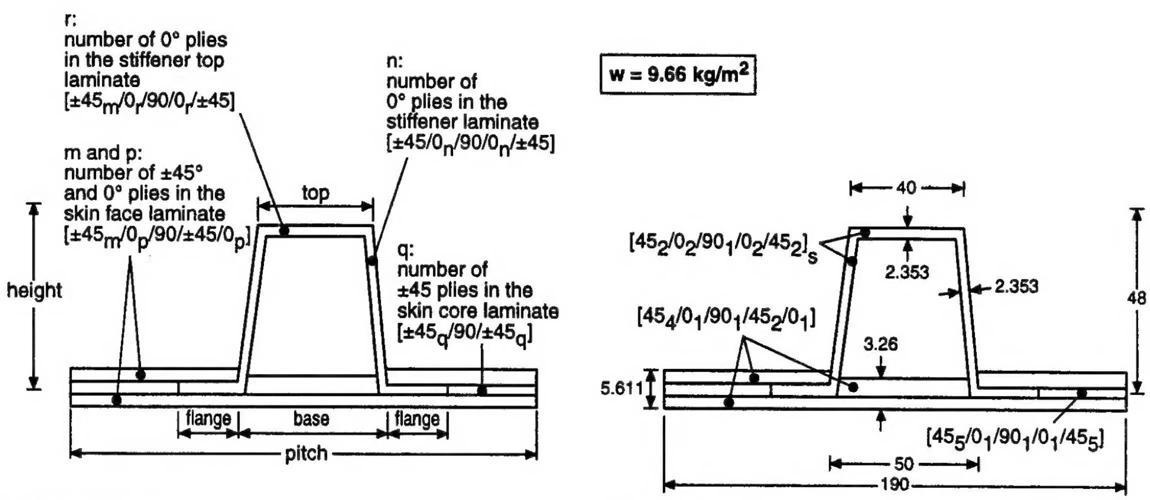


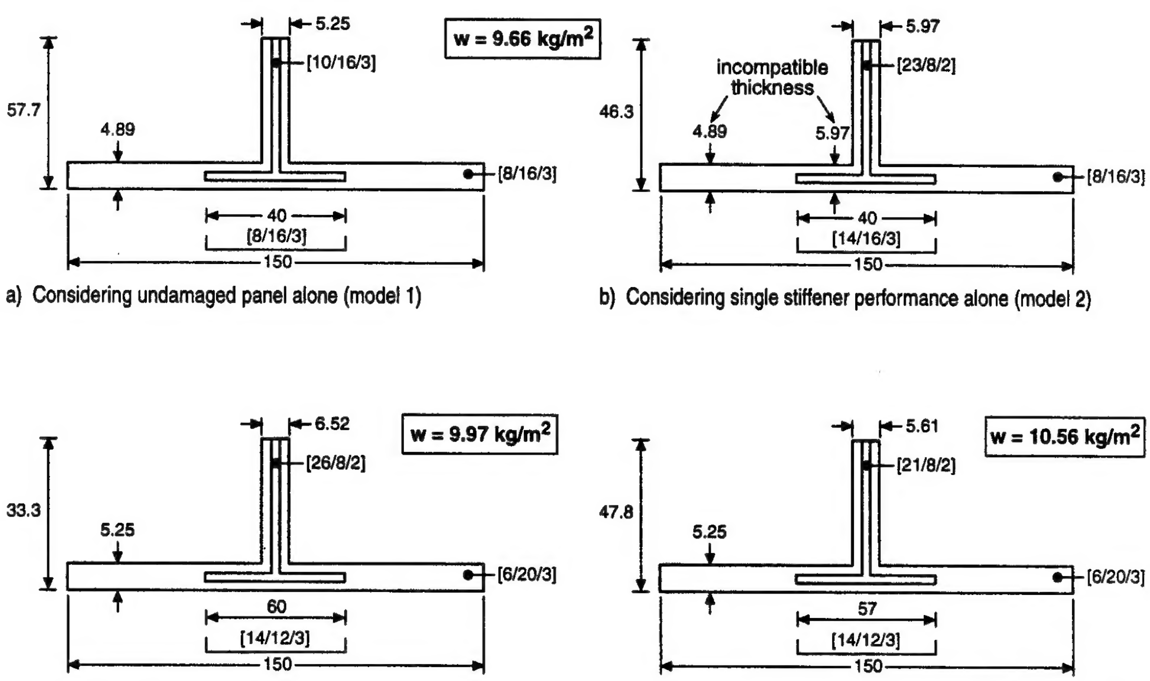
Fig. 3 I-stiffened, flush-skin design (dimensions in mm)



a) Design variables

b) Final configuration

Fig. 4 Hat-stiffened, flush-skin design (dimensions in mm)



a) Considering undamaged panel alone (model 1)

b) Considering single stiffener performance alone (model 2)

c) Considering cut-off stiffener blade alone (model 3)

d) Considering all three configurations simultaneously (model 4)

Fig. 5 Design evolution of stiffened panel with embedded stiffener flanges (laminate code [a/b/c] = [0°/±45°/90°], dimensions in mm)

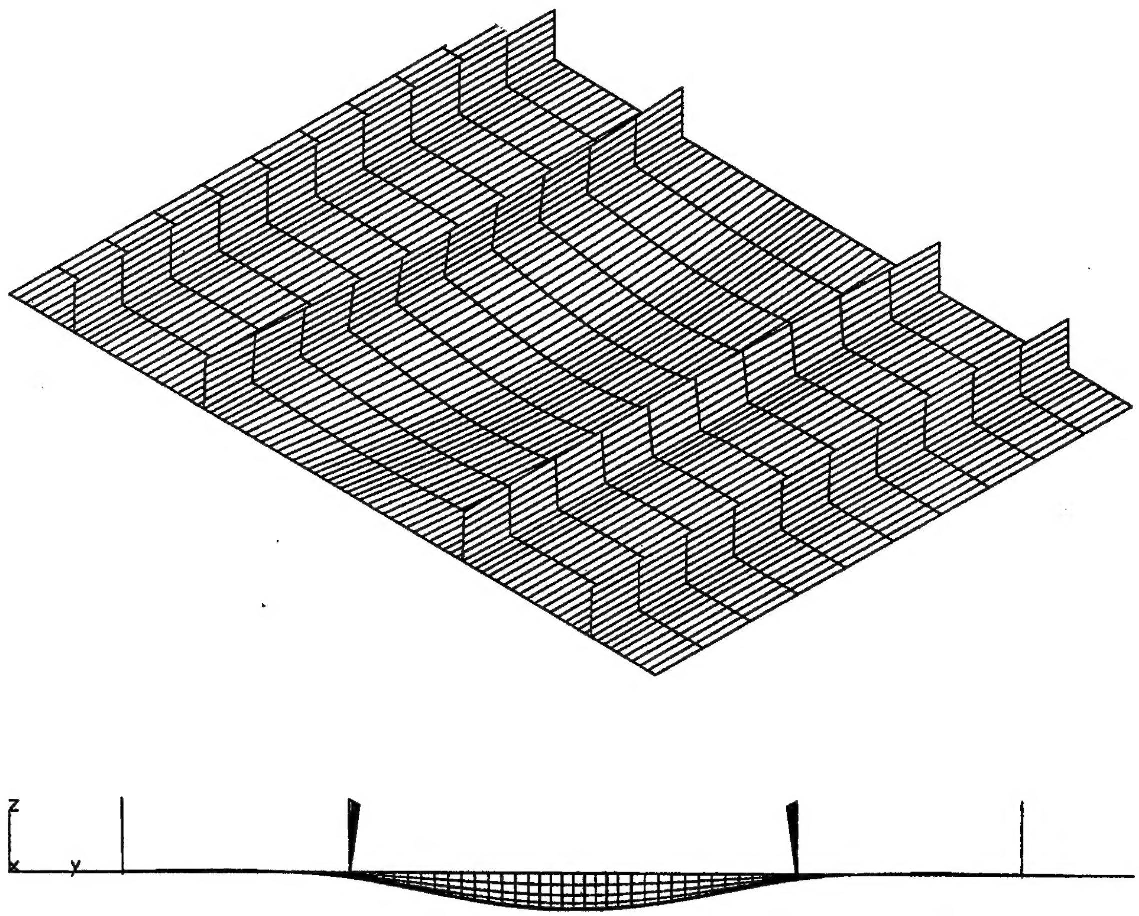
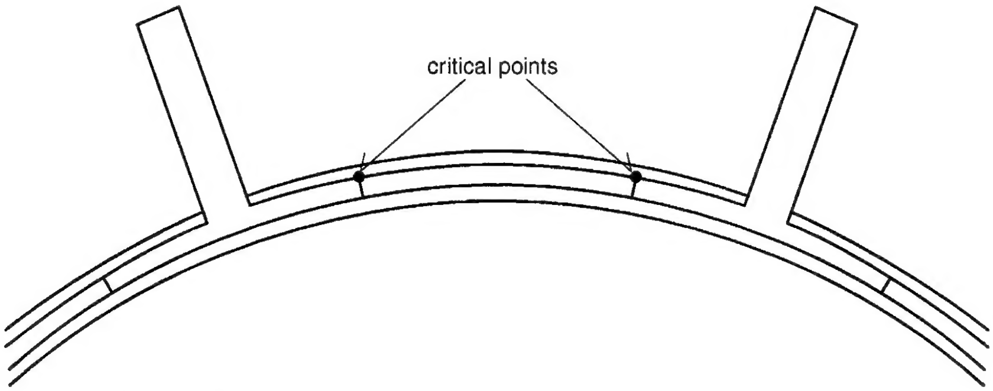
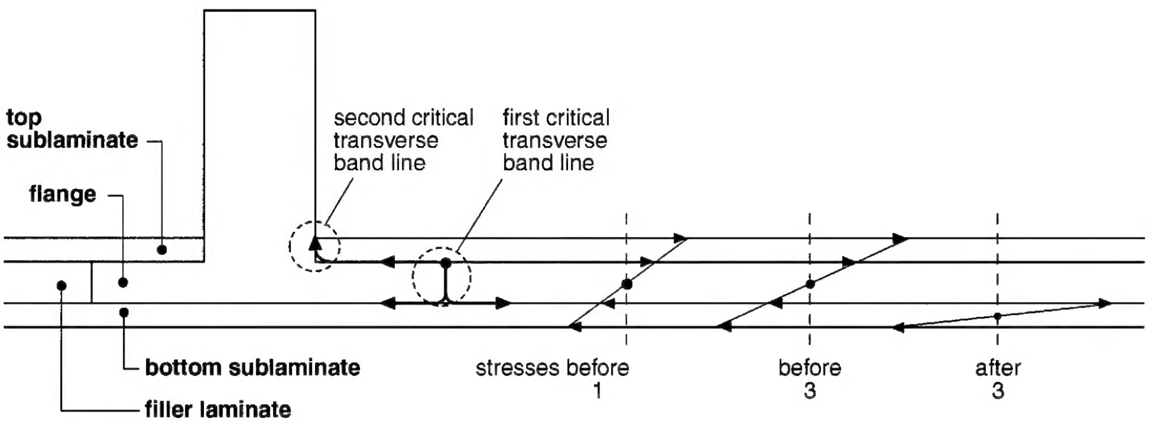


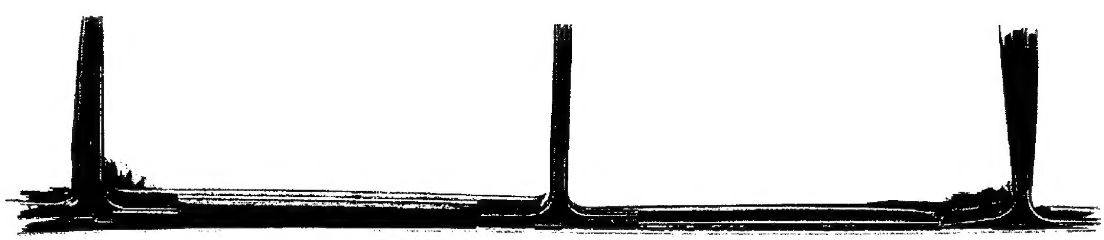
Fig. 6 Single half-wave buckling mode of panel with one cut off stiffener blade



a) Upward bending of the skin



b) Damage spread



c) Post-mortem view

Fig. 7   Failure mechanism